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1. Your reference P34068GB/JJH

2. Patent application number 09 JUL 2002 **0215849.1**
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P01/7700 0.00-0215849.1

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

Switched Reluctance Drives Limited
East Park House
Otley Road, Harrogate,
North Yorkshire, HG3 1PR

07010713001
Patents ADP number *(if you know it)*

If the applicant is a corporate body, give the country/state of its incorporation — United Kingdom

4. Title of the invention

Starting of Switched Reluctance Generators

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

Kilburn & Strode
20 Red Lion Street
London
WC1R 4PJ

Patents ADP number *(if you know it)* 125001 ✓

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
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   b) there is an inventor who is not named as an applicant, or
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Continuation sheets of this form	
Description	11
Claim *(s)*	3
Abstract	1
Drawing *(s)*	6

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Translations of priority documents	
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature Juliet Hibbert Date 9/7/02

12. Name and daytime telephone number of person to contact in the United Kingdom

Hibbert, Juliet Jane Grace
Tel: 020 7539 4200

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Starting of Switched Reluctance Generators

The present invention generally relates to an apparatus and method for starting an electrical generating system. More particularly, the present invention relates to the operation of a switched reluctance generator for generating into a supply system which has no long-term energy storage capabilities.

The characteristics and operation of switched reluctance systems are well known in the art and are described in, for example, "The characteristics, design and application of switched reluctance motors and drives" by Stephenson and Blake, PCIM'93, Nürnberg, 21-24 June 1993, incorporated herein by reference. Figure 1a shows a typical switched reluctance drive in schematic form, arranged to operate as a motor. The switched reluctance machine 12 is connected to a load 19. The DC power supply 11 can be either a battery or rectified and filtered AC mains or some other form of energy storage. The DC voltage provided by the power supply 11 is switched across the phase windings 16 of the machine 12 by a power converter 13 under the control of the electronic control unit 14. The switching must be correctly synchronised to the angle of rotation of the rotor for proper operation of the drive, and a rotor position detector 15 is typically employed to supply signals corresponding to the angular position of the rotor. The rotor position detector 15 may take many forms, including that of a software algorithm, and its output may also be used to generate a speed feedback signal. The presence of the position detector and the use of an excitation strategy which is dependent on the instantaneous position of the rotor leads to the generic description of "rotor position switched" for these machines.

Many different power converter topologies are known, several of which are discussed in the Stephenson paper cited above. One of the most common

configurations is shown for a single phase of a polyphase system in Figure 2, in which the phase winding 16 of the machine is connected in series with two switching devices 21 and 22 across the busbars 26 and 27. Busbars 26 and 27 are collectively described as the "DC link" of the converter. Energy recovery diodes 23 and 24 are connected to the winding to allow the winding current to flow back to the DC link when the switches 21 and 22 are opened. A low-value resistor 28 is connected in series with the lower switch to act as a current-sense resistor. A capacitor 25, known as the "DC link capacitor", is connected across the DC link to source or sink any alternating component of the DC link current (i.e. the so-called "ripple current") which cannot be drawn from or returned to the supply. In practical terms, the capacitor 25 may comprise several capacitors connected in series and/or parallel and, where parallel connection is used, some of the elements may be distributed throughout the converter.

Figure 3 shows typical waveforms for an operating cycle of the circuit shown in Figure 2 when the machine is in the motoring mode. Figure 3(a) shows the voltage being applied at the "on angle" θ_{on} for the duration of the conduction angle θ_c when the switches 21 and 22 are closed. Figure 3(b) shows the current in the phase winding 16 rising to a peak and then falling slightly. At the end of the conduction period, the "off angle" θ_{off} is reached, the switches are opened and the current transfers to the diodes, placing the inverted link voltage across the winding and hence forcing down the flux and the current to zero. At zero current, the diodes cease to conduct and the circuit is inactive until the start of a subsequent conduction period. The current on the DC link reverses when the switches are opened, as shown in Figure 3(c), and the returned current represents energy being returned to the supply. The shape of the current waveform varies depending on the operating point of the machine and on the switching strategy adopted. As is well-known and described in, for example,

the Stephenson paper cited above, low-speed operation generally involves the use of current chopping to contain the peak currents, and switching off the switches non-simultaneously gives an operating mode generally known as "freewheeling".

As is well known in the art, switched reluctance machines can be operated in a motoring mode, as shown in Figure 1a, to drive load 19. In a generating mode, as shown in Figure 1b, the load 19 is replaced by a prime mover 19' to turn the switched reluctance machine and the power supply 11 is replaced with a load 11' for the generated electricity e.g. a storage battery or a device to be driven.

In the generating mode the phase currents are mirror images (in time) of the motoring currents. Such systems are discussed in, for example, "Generating with the switched reluctance motor", Radun, Proceedings of the IEEE 9th Applied Power Electronics Conference, Orlando, Florida, 13-17 Feb 1994, pp 41- 47 incorporated herein by reference. Figure 4(a) illustrates a current waveform when the system is motoring and Figure 4(b) illustrates the corresponding current waveform for generating. Flux is indicated by the dashed line. It will be seen from Figure 4(b) that the machine requires a "priming" or magnetising flux to be established (along with the necessary current to support this flux) before the larger current is returned to the DC link. In other words, some electrical energy is required from the DC link to prime the machine before it is able to convert the larger amount of mechanical energy back to the DC link.

With generating systems which are static (i.e. part of a fixed installation), there is usually a convenient source of energy from which to prime the machine. However some systems are not part of a fixed installation because they are fitted on, for example, marine or automotive equipment, so a special source has

to be provided. In systems where the DC link has a relatively low value (e.g. 12V or 48V), it is conventional to incorporate a storage battery 50 in the system, connected across the DC link as shown in Figure 5(a). This battery is available to provide sufficient energy to prime the phase(s) when the generator is called into action.

In systems where the DC link has a high value (e.g. 300V or more), it is difficult to provide a storage battery at that voltage because of cost and safety implications. Two options have hitherto been available.

Firstly, a low-voltage battery can be used with an up-converter 52, as shown in Figure 5(b). This overcomes many of the safety problems associated with isolation of a high-voltage source, but is costly. In addition, unless the up-converter is bi-directional, some other form of battery charging must be provided to re-charge the battery, entailing further cost.

Secondly, the system can rely on the short-term energy storage provided by the DC link capacitors in the power converter. While this will be successful if the amount of charge left in the capacitors at the time of starting is sufficient to energise the machine adequately, there is no guarantee that the capacitors will hold their charge during an prolonged shut-down. Further, it is often a requirement that capacitors are discharged before any maintenance work is done on the converter, and this would preclude subsequently starting the system by this method.

There is therefore a need for economically starting a generating system on a bus which has no long-term storage. In accordance with a preferred embodiment of the present invention, the foregoing disadvantages of known switched reluctance generators are overcome.

The present invention is defined in the accompanying independent claims. Preferred features of the invention are recited in the claims respectively dependent thereon.

According to a first aspect of the invention there is provided a reluctance machine comprising a rotor having a plurality of rotor poles, a stator having a plurality of stator poles, at least one phase winding for exciting at least two of the poles and a priming winding to excite the poles.

The priming winding is provided to, in use, prime the reluctance machine when it is arranged to operate as a generator. This is achieved by arranging the priming winding to be connected, in use, to a power supply to excite the poles and to cause time-varying flux linkage in the or each phase windings. In use, the priming winding is then subsequently de-energised and the phase winding(s) used to excite the poles.

Thus, in use as a generator, the machine is primed using the priming winding and, once steady state operation is reached, the priming winding is switched out and the machine excited by energising the phase winding(s).

This allows the a switched reluctance drive to be operated as a generator on a high voltage supply which has no long-term energy storage capability. A low voltage supply is used to start the generator through the use of a dedicated priming winding, which provides sufficient energy to allow the generator to build up charge in one or more DC link capacitors. Once sufficient charge has built up, the priming winding is de-energised and the generator continues in a steady-state operation. Unidirectional currents are carried by both the phase winding(s) and the priming winding(s).

Preferably the priming winding is connectable to a power source separate from that used to excite the phase windings.

The reluctance machine is advantageously a switched reluctance machine, in particular operated as a generator.

The phase winding(s) are preferably provided on the stator poles and the priming winding is also provided on the stator.

The priming winding may extend along a longitudinal axis of the stator or the priming winding may be of a gramme-ring type, wound around a back iron part of the stator, or the priming winding may be provided around at least one of the stator poles.

Preferably the phase windings are excitable by a DC link, the ratio of the voltage of the DC link to the supply voltage for the priming winding being greater than 3.

A reluctance machine according to any preceding claim further comprising means for connecting the primary winding to a source of priming electrical energy, the connecting means comprising a switch, a chopper unit or a current controller.

Preferably the priming winding and its associated priming power source, and switching components if any, are rated for short-term use, so reducing the cost of implementation.

In a second aspect of the invention there is provided a method of starting a

switched reluctance generator comprising a rotor having a plurality of rotor poles and a stator having a plurality of stator poles, at least one phase winding defining one or more phases, and at least one priming winding, the method comprising: driving the rotor relative to the stator; energising the priming winding by forming an electrical connection between the priming winding and a source of electrical energy to excite two or more of the poles and to cause time-varying flux linkage in the or each phase windings and subsequently de-energising the priming winding.

Thus the generator is primed using the priming winding and, once steady state operation is reached, the priming winding is switched out (or de-energised) and the generator excited by energising the phase winding(s) of the generator.

Preferably the switched reluctance generator is connected to a DC link and the priming winding is de-energised once the DC link voltage has reached a pre-determined value and the phase winding(s) of the generator are then energised solely from the DC link.

Preferably the DC link has a DC capacitor which is connectable across the or each phase winding. The DC link capacitor is charged by supplying current from the or each phase winding to the DC link capacitor and the priming winding is disconnected from the source once the voltage of the DC link capacitor has reached a pre-determined value.

Other aspects and advantages of the invention will become apparent upon reading the following detailed description of exemplary embodiments of the invention and upon reference to the accompanying drawings, in which:

Figure 1 is a schematic drawing of a prior art switched reluctance drive;

Figure 2 is a prior art excitation circuit for the switched reluctance machine of

Figure 1;

Figure 3(a) is a phase voltage waveform for the circuit shown in Figure 2;

Figure 3(b) is the phase current waveform corresponding to Figure 3(a);

Figure 3(c) is the supply current waveform corresponding to Figure 3(a);

Figure 4(a) and Figure 4(b) show motoring and generating current waveforms respectively;

Figure 5(a) shows a prior art generating system;

Figure 5(a) shows a prior art generating system with an up-converter;

Figure 6 shows the schematic arrangement of windings in an embodiment of the invention;

Figure 7 shows the winding arrangement in another embodiment of the invention;

Figure 8 shows the winding arrangement in a yet further embodiment of the invention; and

Figure 9 shows a switched reluctance drive system according to one embodiment of the invention.

The Radun paper cited above discloses a starting method for a switched reluctance generator, whereby the excitation energy initially comes from a battery supplying an excitation bus for the phase windings of the machine. The generator returns all its output to that bus until the bus voltage rises to a suitable level, whereupon extra thyristor switches are closed to supply the output of the generator to the load. Steady state operation entails the use of both excitation buses and the extra thyristors. A similar system with split excitation and load buses is disclosed in EPA 0564067.

By contrast with these prior art systems, the present invention uses a single bus and a separate priming winding which is used to pump up the voltage on the DC link capacitors. The system will now be described in detail.

Figure 6 shows a cross section of a switched reluctance machine suitable for use with the invention. The machine has three phase windings 63 assembled on stator poles 61 of the phases A, B and C. The rotor 66 has rotor poles 64 and is mounted on a shaft 68. The stator also carries a priming winding 65, which in this embodiment is full-pitched across the machine, embracing the poles of all the phases, and extending along the longitudinal axis of the stator.

Other embodiments of the priming winding are possible. For example, Figure 7 shows the embodiment of a gramme-ring type winding 65, wound around the back iron of the stator. This arrangement may be appropriate in some systems where the outer surfaces of the stator are not used as an interface to another component. Figure 8 shows the priming winding 65 distributed on the stator poles 61. Note that, in the example shown in Figure 8, all the stator poles are used, though this is not strictly necessary. Nor is it necessary that there is close coupling between the main phase winding 63 and the priming winding 65, unlike a bifilar winding arrangement where the windings are physically arranged to have the highest possible mutual coupling.

It will be appreciated that, although a 3-phase system has been used for illustration, this is purely exemplary and the principles outlined above apply to any number of phases and any combination of numbers of stator and rotor poles.

Whatever physical arrangement is adopted for the priming winding, the winding is electrically connected to a separate supply 92, as shown in Figure 9, by a connecting means 94 under the control of the control system 14'. The priming winding 65 is shown schematically in arrangement with the switched reluctance machine 12'. The connecting means 94 can be a simple mechanical

switch or relay, in which case the current flowing in the winding will be largely controlled by the resistance of the priming winding 65. If the resistance is too small to limit the current to a suitable value, either because the resistance is low or the supply 92 is relatively high, then connecting means 94 can be a chopper unit or other form of current controller as known in the art.

It will be noted that in this embodiment there is no electrical connection between the priming winding and the phase windings of the machine, i.e. there is galvanic isolation between them. This is a significant benefit from a safety viewpoint.

In operation, the prime mover 97 will drive the generator by rotating the rotor at some appropriate speed relative to the stator. To start the generator, the priming winding 65 is energised by the control system causing the supply 92 to be connected to the priming winding 65 by operating the connecting means 94. Current flows in the priming winding 65, causing a standing flux to be set up in the machine. This flux will pass through whichever stator pole pair(s) are adjacent to rotor poles, since the flux will naturally prefer to flow in those magnetic circuits with the lowest reluctance. However, since the rotor is turning under the influence of the prime mover, different pole pairs will be preferred at different times, so that a time varying flux is seen by any one pole pair. This flux links the phase windings 63 and so induces a time varying, bi-directional voltage in them. Although the switches 21 and 22 associated with the phase windings remain open, the diodes 23 and 24 of the power converter 13 are still connected, and so they act to rectify the voltage, allowing half cycles of current to flow onto the DC link. Since the switches 21 and 22 are open, the current flows into the DC link capacitor 25, raising its voltage at a rate determined by the current and the capacitor size.

When the DC link voltage has been built up to an appropriate level, the priming winding 65 is disconnected from its supply 92 (de-energised) and thereafter is not used in the operation of the generator. The generator can then be excited, in conventional fashion, from the DC link capacitor 25 via the switches 21 and 22 and the main phase windings 63 and the generator output can then be connected to the electrical load 96 via the output switch 98.

This system can therefore generate onto the DC link even though there is no long-term energy storage on it. Preferably the supply 92 is low compared with the DC link, e.g. 12V compared with 300V. The source 92 may be either a primary cell replaced when used or a rechargeable source. Preferably the priming winding 65 is rated only for short term operation, thus saving manufacturing cost and taking up negligible space in the machine.

It will be seen that the priming winding 65 is dedicated to the sole purpose of starting the generator, i.e. providing a means of raising the DC link capacitor 25 to a voltage at which it can supply the excitation needed to the phase winding(s) 61 for steady state operation of the generator. After the DC link capacitor has reached the appropriate value of voltage, the priming winding 65 is disconnected and has no further duty to perform in steady state operation of the generator.

The skilled person will appreciate that variation of the disclosed arrangements are possible without departing from the invention. Accordingly, the above description of several embodiments is made by way of example and not for the purposes of limitation. It will be clear to the skilled person that minor modifications can be made to the arrangements without significant changes to the operation described above. The present invention is intended to be limited only by the scope of the following claims.

Claims

1. A reluctance machine comprising a rotor having a plurality of rotor poles, a stator having a plurality of stator poles, at least one phase winding for exciting two or more of the poles and a priming winding to excite two or more of the poles.

2. A reluctance machine according to claim 1 wherein the priming winding is connectable to a priming power source separate from that used to excite the phase windings.

3. A reluctance machine according to claim 1 or 2 wherein the machine is a switched reluctance machine.

4. A reluctance machine according to claims 1, 2 or 3 wherein the phase windings are provided on the stator poles.

5. A reluctance machine according to any of claims 1 to 4 wherein the priming winding is provided on the stator.

6. A reluctance machine according to claim 5 wherein the priming winding extends along a longitudinal axis of the stator.

7. A reluctance machine according to claim 5 wherein the priming winding is of a gramme-ring type, wound around a back iron part of the stator.

8. A reluctance machine according to claim 5 wherein the priming winding is provided around at least one of the stator poles.

9. A reluctance machine according to any preceding claim wherein the

phase windings are excitable by a DC link, the ratio of the voltage of the DC link to the supply voltage for the priming winding being greater than 3.

10. A reluctance machine according to any preceding claim further comprising means for connecting the primary winding to a priming power source, the connecting means comprising a switch, a chopper unit or a current controller.

11. A reluctance machine according to any preceding claim wherein the priming winding and/or its associated priming power source, and/or connecting components if any, are rated for short-term use.

12. A method of starting a switched reluctance generator comprising a rotor having a plurality of rotor poles and a stator having a plurality of stator poles, at least one phase winding defining one or more phases, and at least one priming winding, the method comprising;

driving the rotor relative to the stator;

energising the priming winding by forming an electrical connection between the priming winding and a source of electrical energy to excite two or more of the poles and to cause time-varying flux linkage in at least one of the phase windings and subsequently de-energising the priming winding and energising the phase winding(s) of the generator.

13. A method according to claim 12 wherein the switched reluctance generator is connected to a DC link and further comprising de-energising the priming winding once the voltage of the DC link has reached a pre-determined value and subsequently energising the phase

winding(s) of the generator from the DC link.

14. A method according to claim 13 in which the DC link has a DC capacitor connected across the phase winding(s), the method further comprising:

charging the DC link capacitor by supplying current from the or each phase winding to the DC link capacitor and disconnecting the priming winding from the source once the voltage of the DC link capacitor has reached a pre-determined value.

ABSTRACT:

A switched reluctance drive 12' is operated as a generator on a high voltage supply which has no long-term energy storage capability. A low voltage supply 92 is used to start the generator through the use of a dedicated priming winding 65, which provides sufficient energy to allow the generator to build up charge in DC link capacitor(s). Once sufficient charge has built up, the priming winding is de-energised and the generator continues in a steady-state operation.

Fig. 9

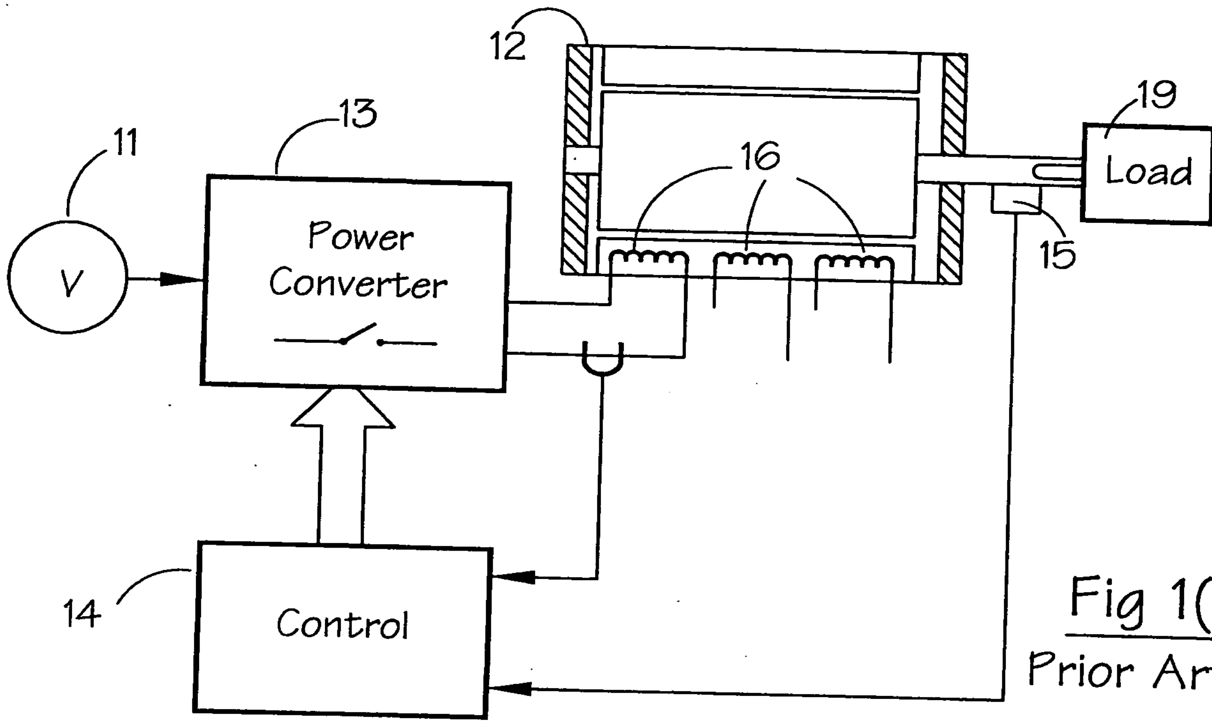

Fig 1(a)
Prior Art

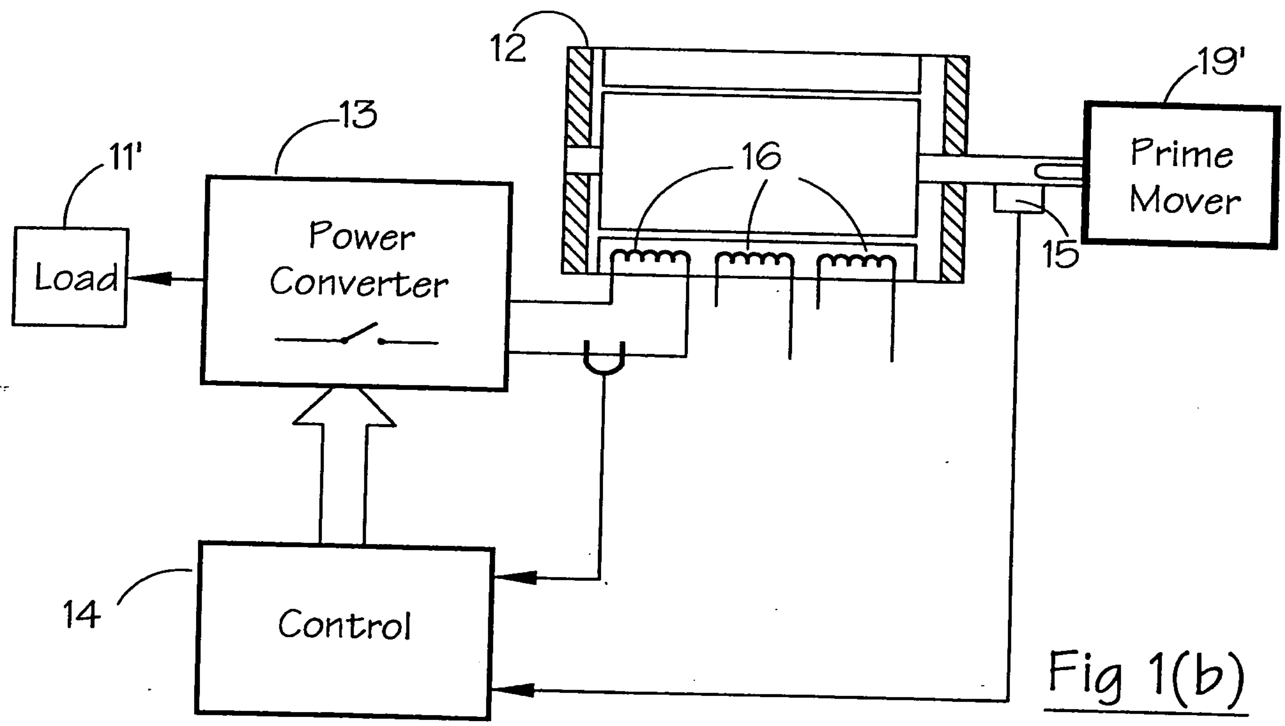

Fig 1(b)
Prior Art

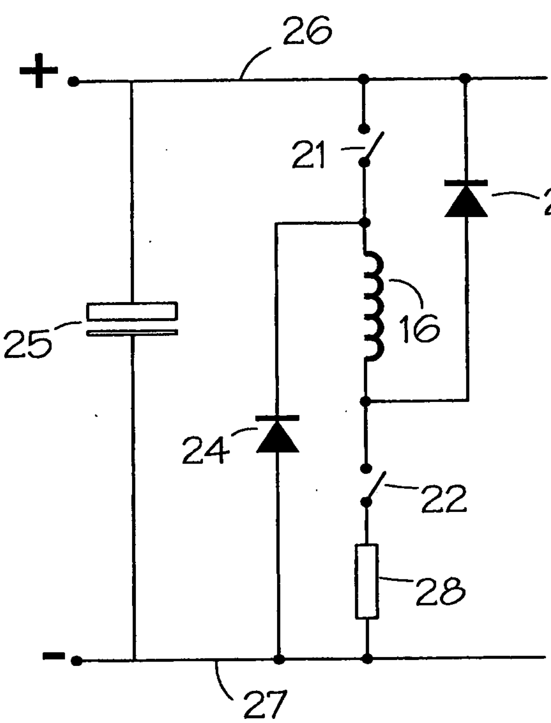

Fig 2
Prior Art

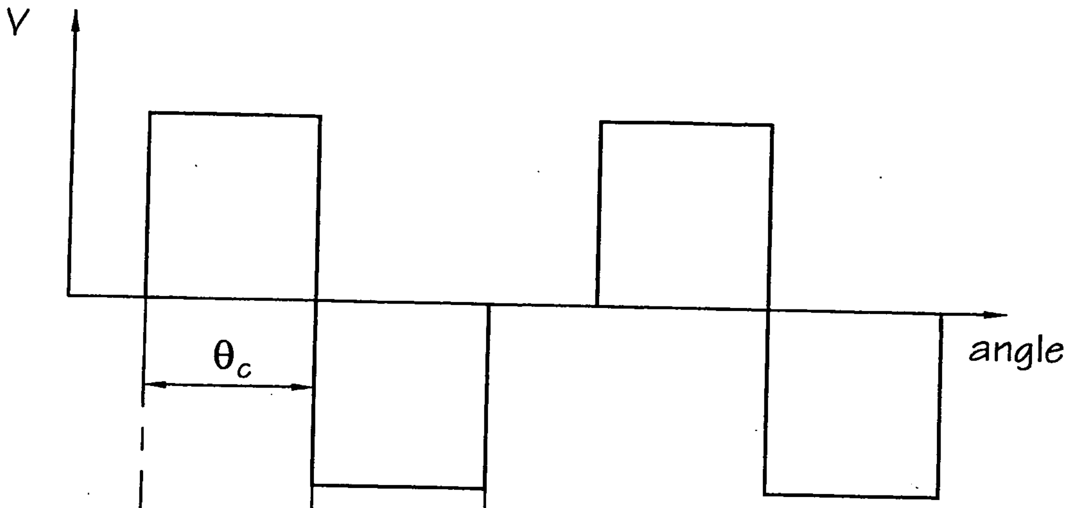

Fig 3(a)

Prior Art

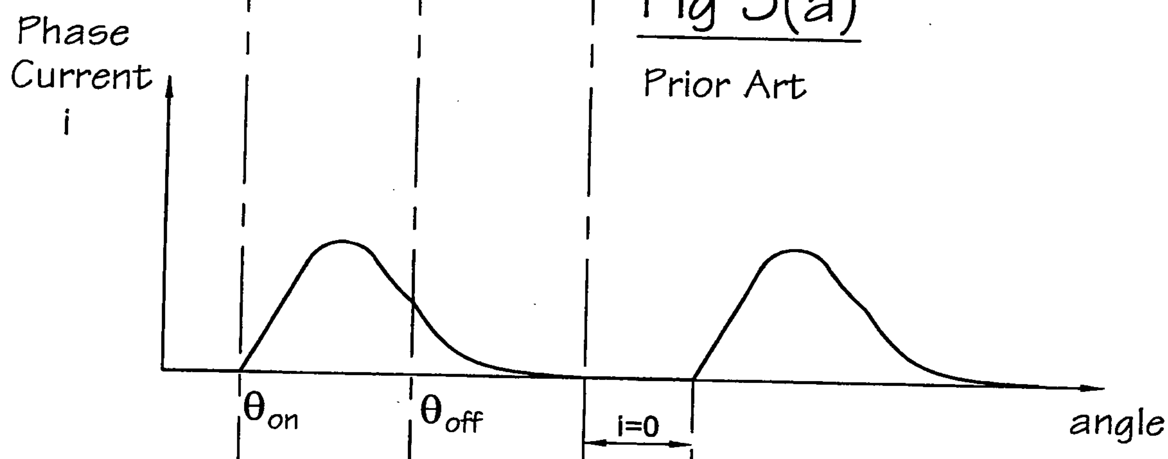

Fig 3(b)

Prior Art

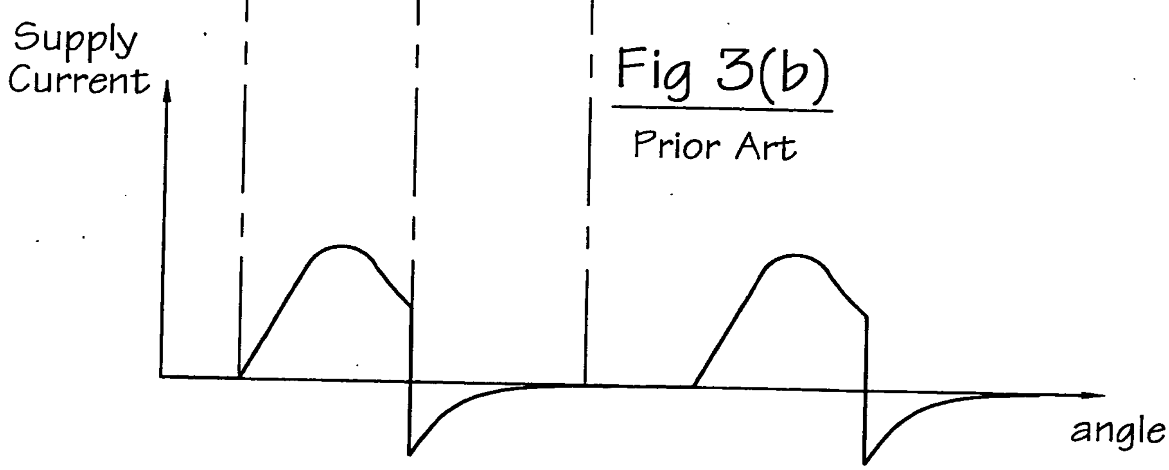

Fig 3(c)

Prior Art

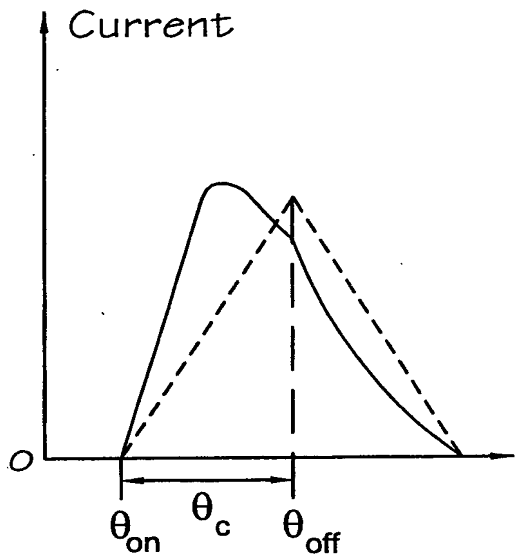

Fig 4a
Prior Art

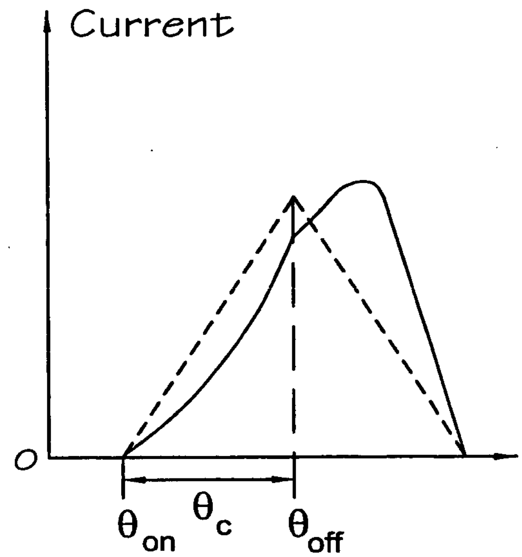

Fig 4b
Prior Art

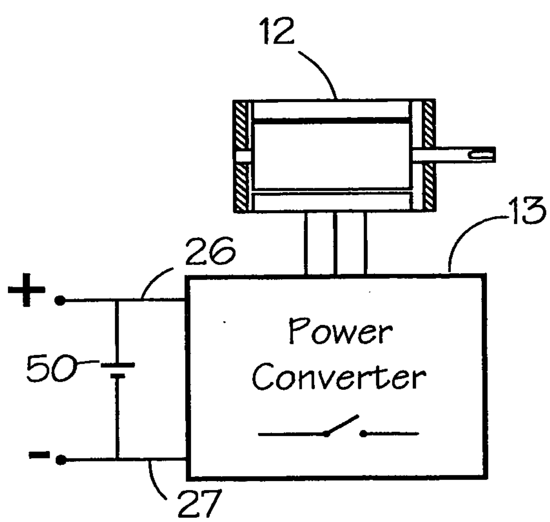

Fig 5a
Prior Art

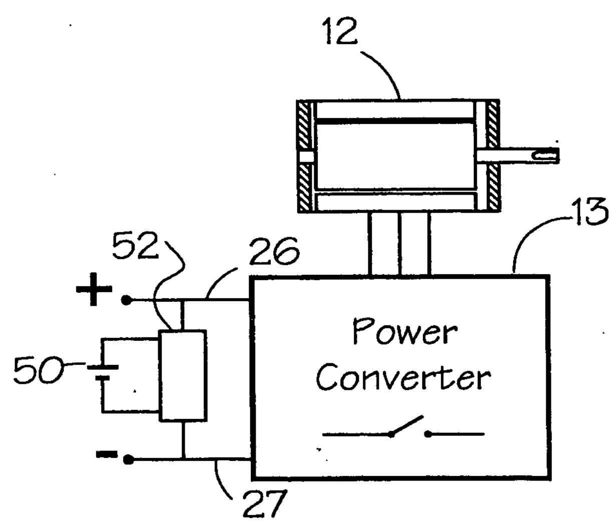

Fig 5b
Prior Art

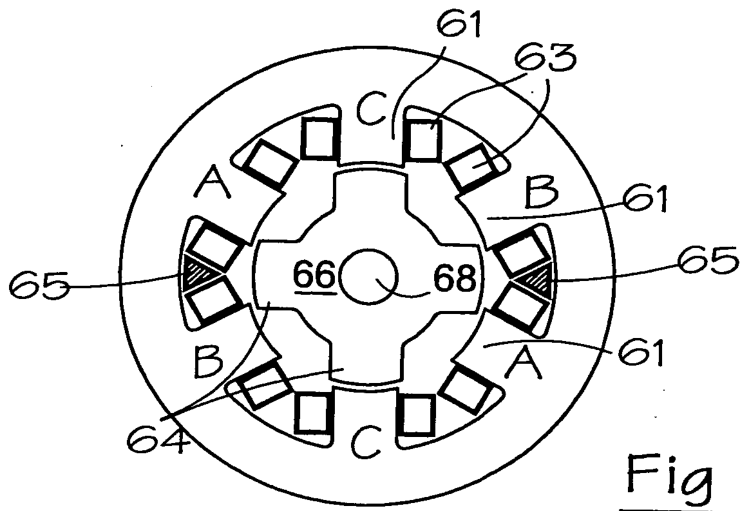

Fig 6

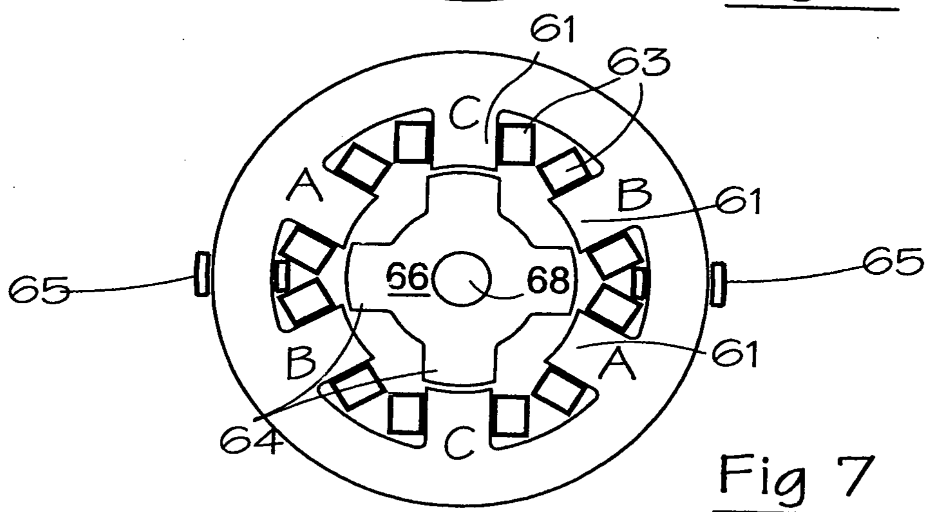

Fig 7

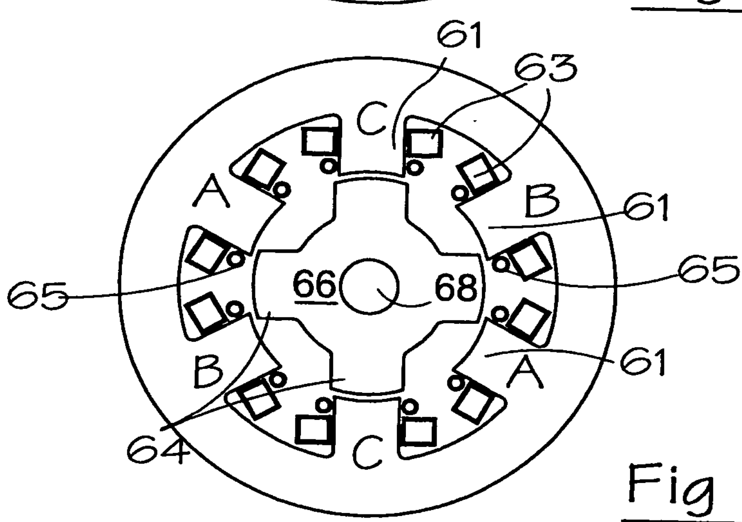

Fig 8

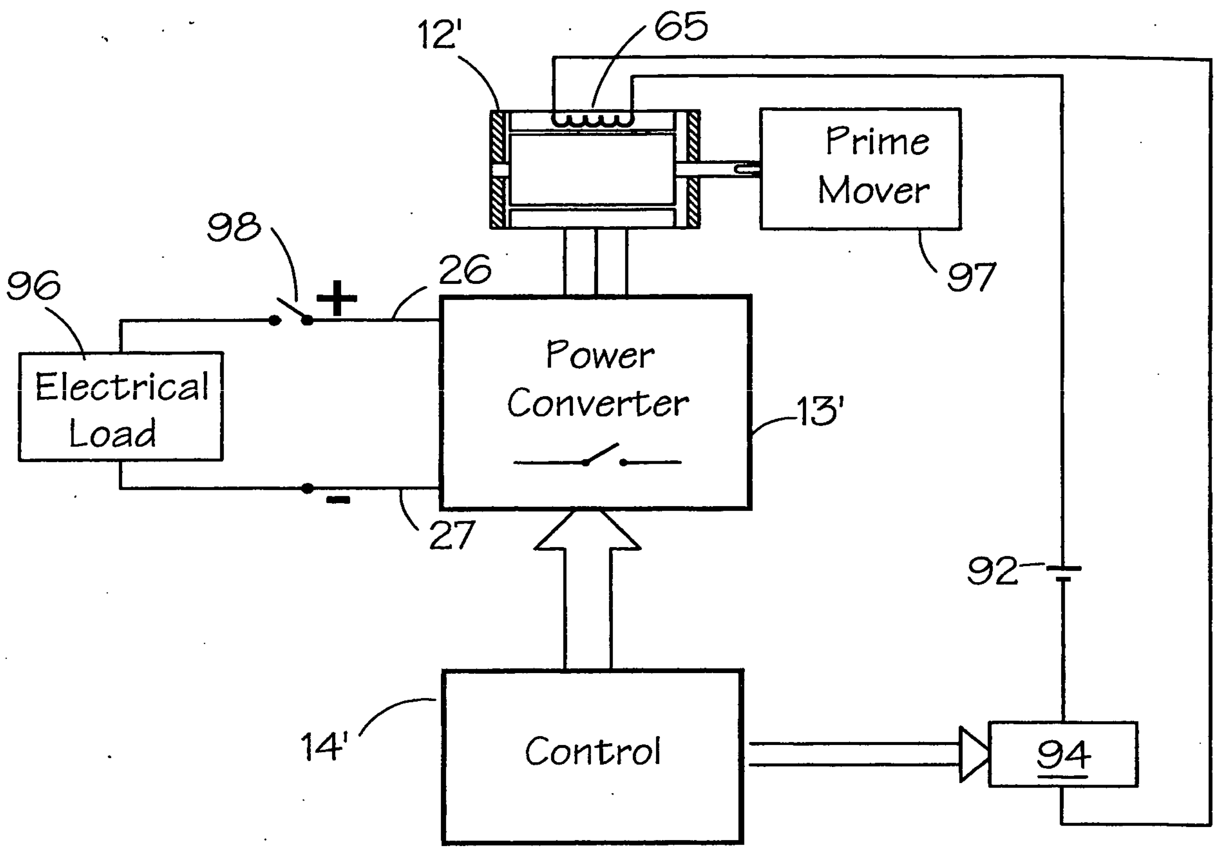
12'
65
Prime Mover
97
98
96
26
+
Electrical Load
Power Converter
13'
-
27
92
14'
Control
94

Fig 9